Supernova Remnants and the Interstellar Medium

also known as

Diffuse X-ray Analysis

Randall Smith

- The Interstellar Medium
- Phases of the ISM
- X-ray studies of the Hot ISM
- Supernovae and Supernova Remnants
  - Theory
  - Evolutionary Phases
  - X-ray Emission
  - Analysis Methods
  - Modelling the X-ray Emission
  - Non-Equilibrium Models

This ISM is:

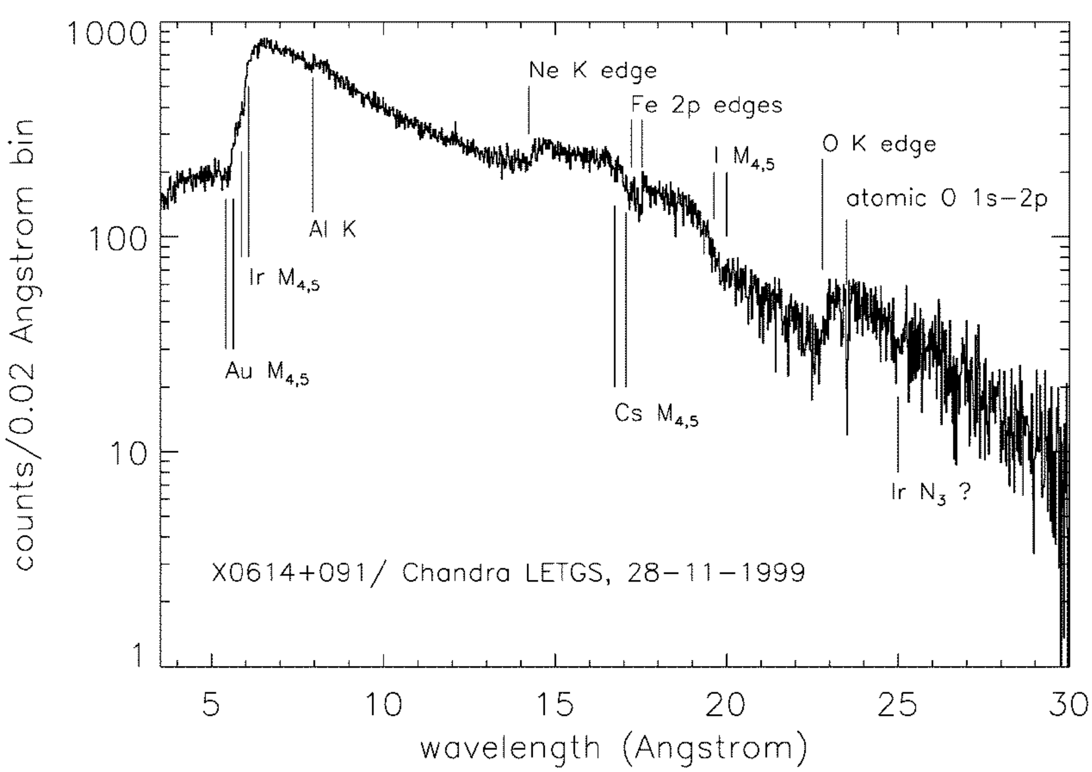
- Chock-full of gas and dust in various semi-random clumps
- Poorly understood at best
- A crucial component of all astronomical observations beyond the solar system.

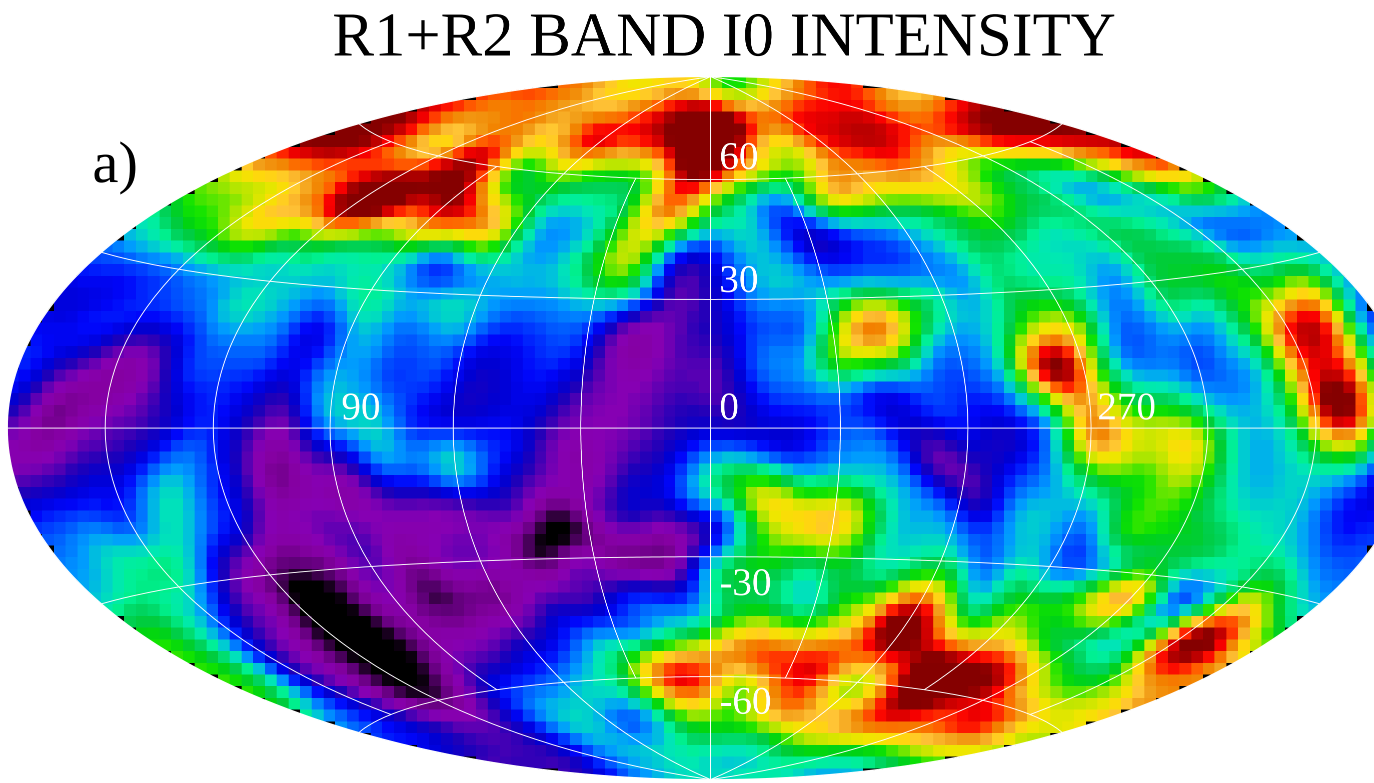
The ISM has a number of phases:

- Cold Neutral Medium / Molecular Clouds : $T \sim 100\,\mathrm{K}$, $n \sim 100 - 10^4\,\mathrm{cm}^{-3}$
- Warm Neutral Medium: $T \sim 1000\,\mathrm{K}$, $n \sim 1\,\mathrm{cm}^{-3}$
- Warm Ionized Medium: $T \sim 10,000\,\mathrm{K}$, $n \sim 0.1\,\mathrm{cm}^{-3}$
- Hot Interstellar Medium: $T \sim 10^6\,\mathrm{K}$, $n \sim 0.01\,\mathrm{cm}^{-3}$

Unsurprisingly, only the hot ISM emits any X-rays, and even these are easily absorbed since they are so soft.

All the phases of the ISM can be studied using absorption spectroscopy. Simply find a bright (ideally continuum) source, and look for absorption features (from Paerels et al 2001):

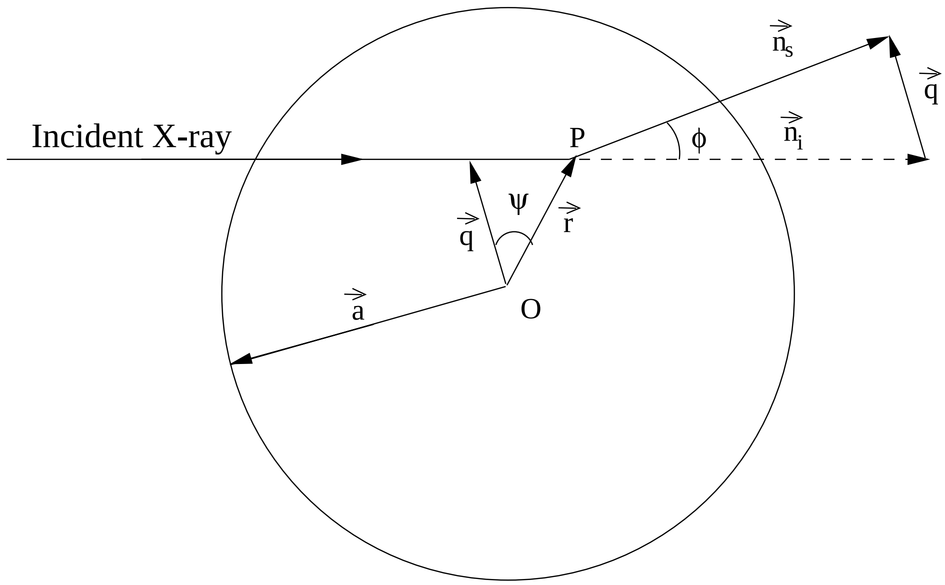




This plot (from Snowden *et al.*, 1997), shows the foreground emission in the ROSAT R1+R2 bands after fitting the entire dataset to an absorption model. Even after removing external sources, there is still leaves a substantial local component, which retains a halo/plane asymmetry.

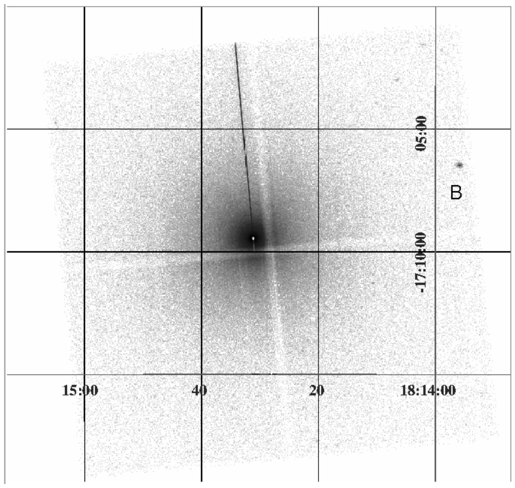
We can study IS dust grains using X-rays. Dust grains cause X-rays to scatter very slightly as the X-ray passes through the grain.

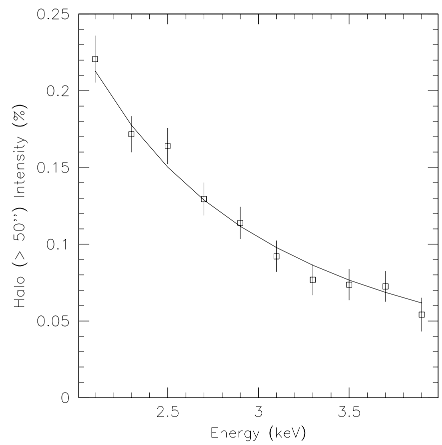
What causes the scattering?



The X-ray photon sees the dust particle as a cloud of free electrons, each one a scattering site. Assuming each electron "sees" the wave (photon), it will oscillate like a dipole at the wave frequency–ie, Rayleigh scattering.

When the scattered waves add coherently, the scattering amplitude is $\propto N^2$. Otherwise, the amplitude is only $\propto N$.





[Left] The highly-absorbed LMXB GX13+1, as viewed with Chandra's ACIS imager
After the PSF is removed, and the halo intensity (as a fraction of source intensity) is extracted as a function of energy, giving $I(E) = 1.5^{+0.5}_{-0.1} E^{-2}$.

This can be related to the underlying dust model as follows

$$I(E) = 80.7 \left(\frac{\mathrm{N_H}}{10^{22}\mathrm{cm}^{-2}}\right) \left(\frac{\rho}{3\,\mathrm{g\ cm}^{-3}}\right) E_{\mathrm{keV}}^{-2} \int da\, n(a) \left(\frac{a}{0.1\mu\mathrm{m}}\right) \frac{m_{gr}(a)}{m_{\mathrm{H}}} \quad (1)$$

What answers do astronomers want from supernova remnants (SNRs)?

- What is the environment do they explode into like?
- What are the physical interactions at the shock front
- What is the physical state of the ejecta?
- What is left behind?
- What processes govern the late-term evolution?

How can we get these answers? Fortunately for X-ray astronomers, most of the emission from SNRs comes in the form of X-rays. Unfortunately, with the loss of Astro-E, we must primarily use CCD imagers, except for those SNRs small enough to do useful grating observations with Chandra or XMM/Newton. Therefore we can only measure strong lines, observable even when substantially broadened.

Supernovae are gigantic, $E = 10^{53}$ erg explosions.

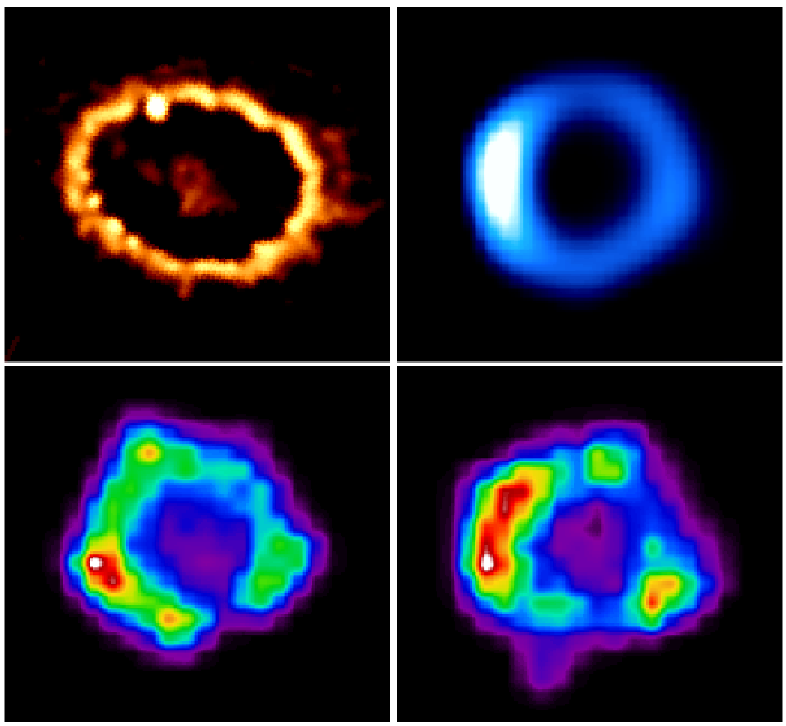
Only 1% of the energy is kinetic; the rest is in neutrinos

As noted by Sedov, Taylor (and von Neumann, albeit in secret), all explosions are fundamentally the same. They go through the following phases:

- Free expansion
- When $M_{swept} \approx M_{ejecta}$, the blast-wave (Sedov) phase begins
- Pressure Conservation (Snowplow) phase: SNR Middle age
- Momentum Conservation

Supernovae

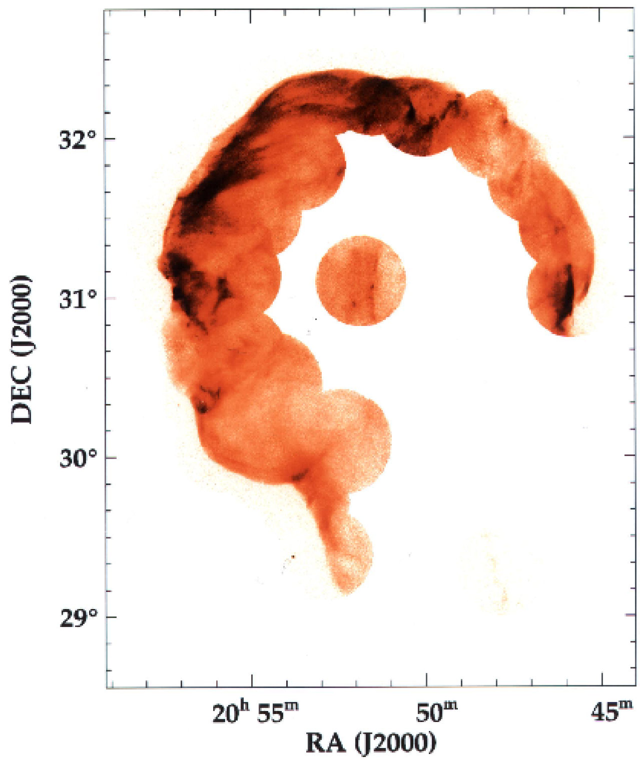
- The Free-Expansion phase, right after explosion
- Normally applied only to explosions detected recently ($<$ 10 years)



SN 1987 A as observed with HST, ATCA, Chandra (1999), Chandra (2000)

Shell-type Remnants

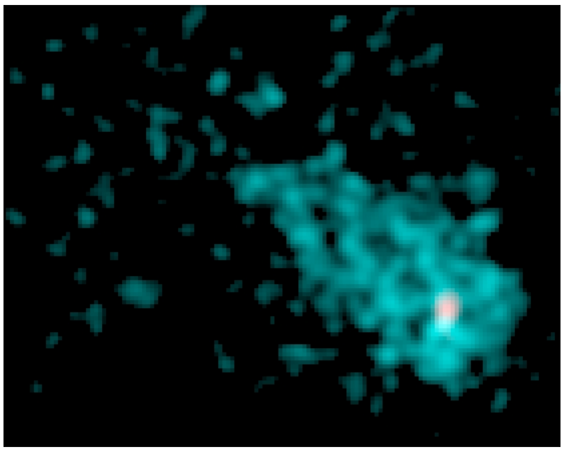
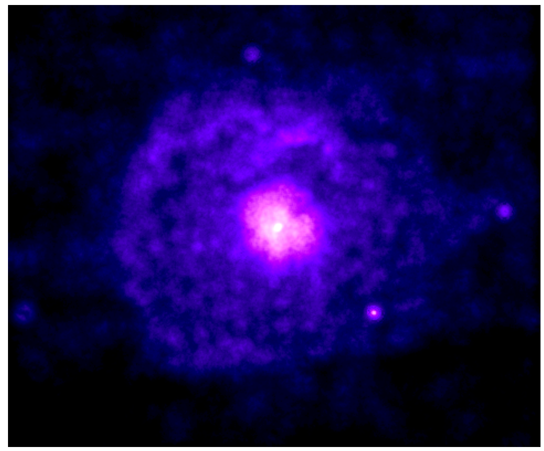
- Shell-like remnant in the X-ray and radio
- X-ray emission is thermal or synchrotron
- X-ray emission not ejecta-dominated



The Cygnus Loop (Levenson 1997) observed with the ROSAT HRI

Plerionic/Center-Filled Remants

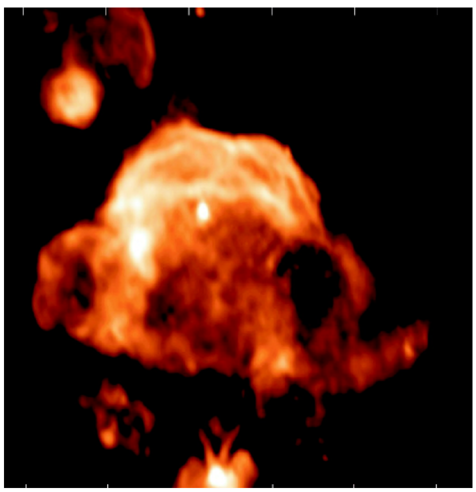
- Centrally-filled X-ray morphology
- Shell-like remnant in the radio
- X-ray emission is synchrotron, not not ejecta-dominated

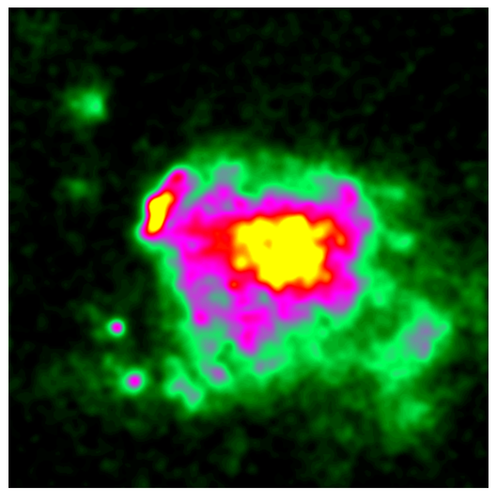



[Left] IC443 from Olbert et al. (2001)
[Right] G21 from Slane et al. (2000)

Thermal Composite/Mixed-Morphology Remnants

- Centrally-filled X-ray morphology
- Shell-like remnant in the radio
- X-ray emission is thermal, not synchrotron
- X-ray emission not ejecta-dominated

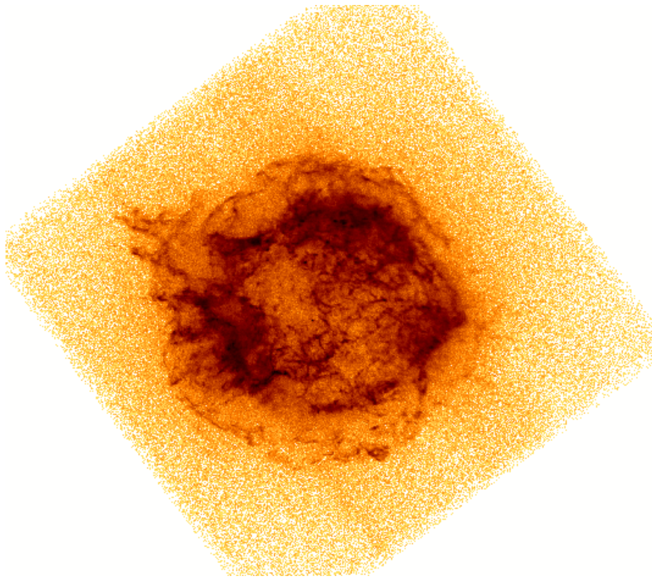


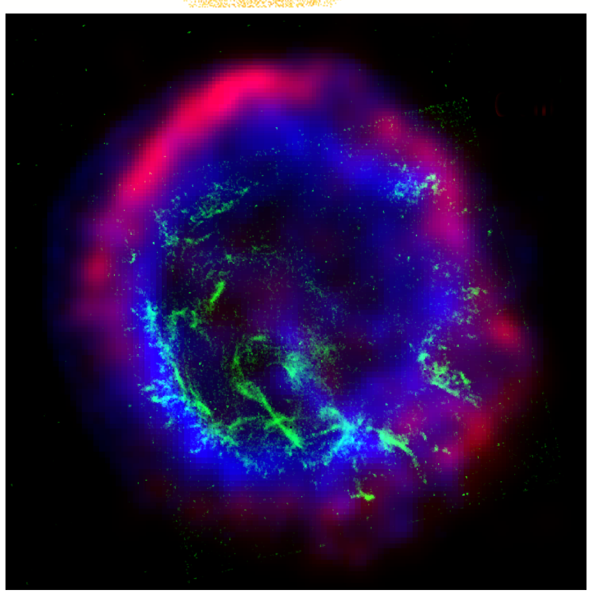


[Left] W28 : 1415 MHz image from Dubner *et al.* 2002
[Right] W28 : ROSAT X-ray image courtesy P. Slane.

Ejecta-Dominated Remnants

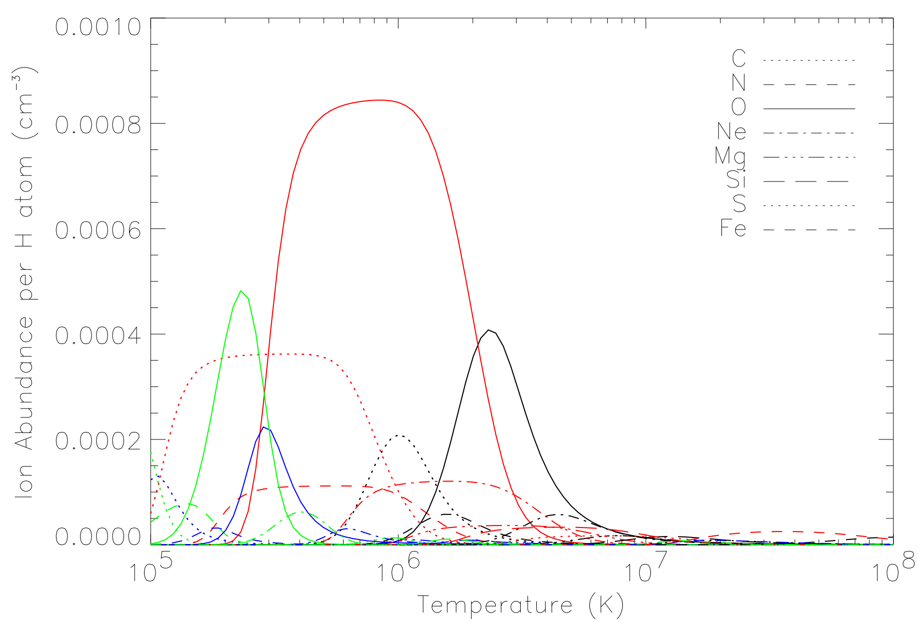
- X-ray emission is ejecta-dominated

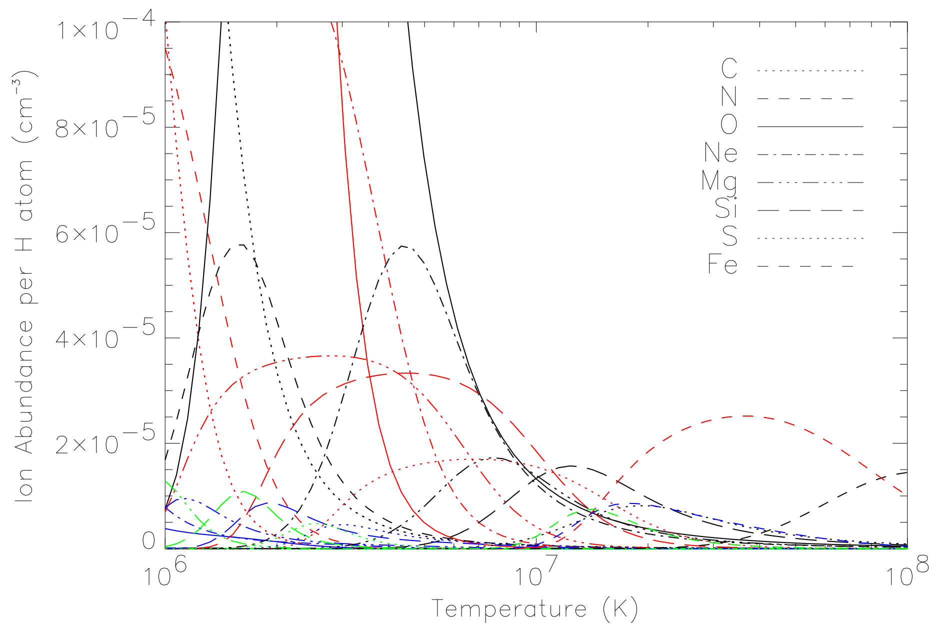




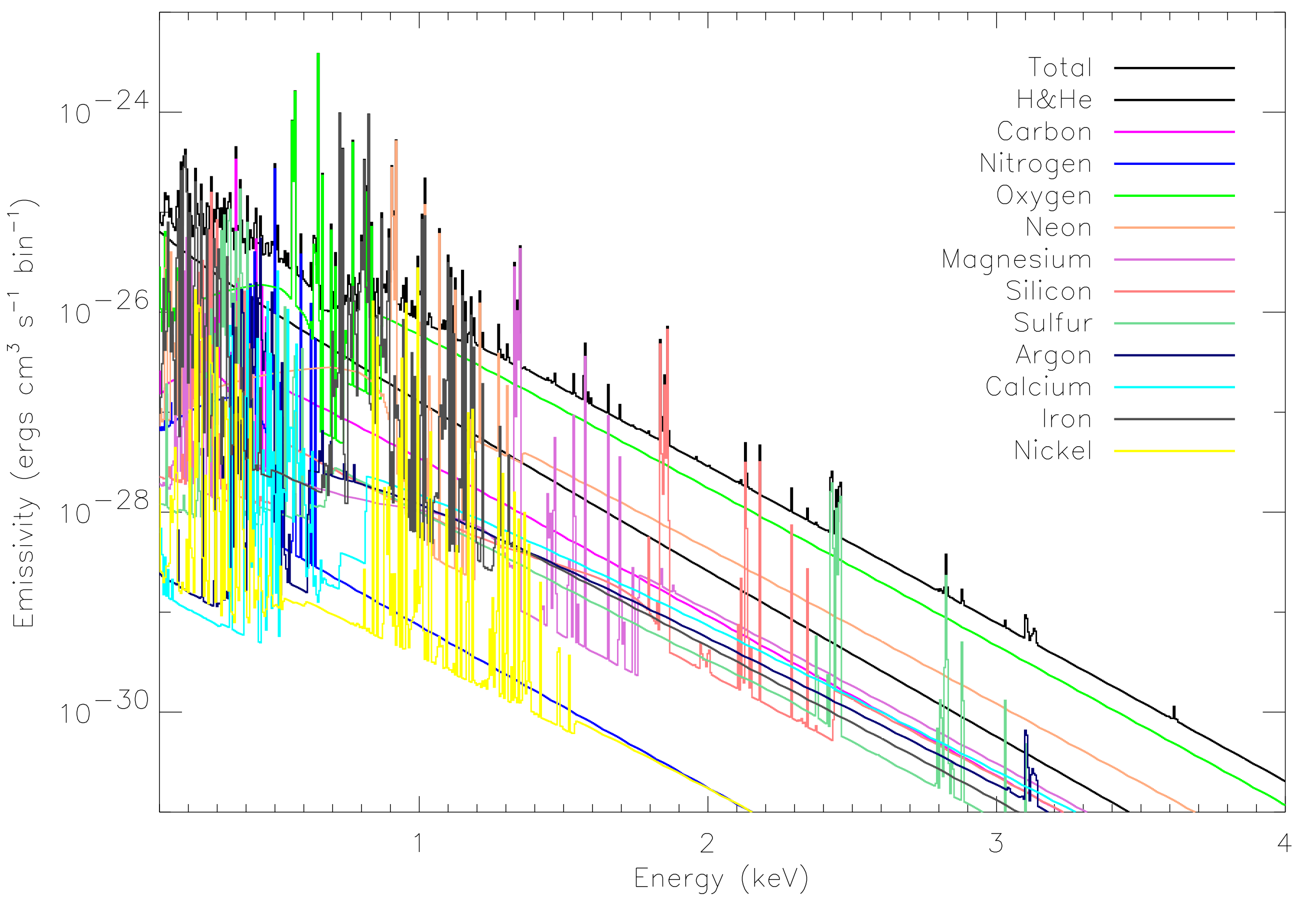
[Left] The Chandra AO1 observation of Cas A
[Right] X-ray: NASA/CXC/SAO, Optical: NASA/HST , Radio: CSIRO/ATNF/ATCA

The primary diagnostic emission lines are from hydrogenic and helium-like ions. Part of the reason why can be seen below:





Shown here is the X-ray spectrum of a CIE plasma at 3×10^6 K, with each element shown as a different color. Note that each ion emits only a few strong lines–so only these will be significant when doing a variable abundance fit.



With the improved spectral resolution of Chandra and XMM/Newton we will be able to extract these individual strong lines from the spectrum–admittedly with large errors at times Diagnostics are usually created from line ratios, since they are much cleaner than whole-spectrum fits.

The emissivity of a given transition line $\lambda_{j\to i}$ is simply

$$\epsilon = \frac{hc}{\lambda_{j\to i}} N_j A_{ji} \tag{2}$$

where N_j is the population of level j and A_{ji} is its transition rate. Nice and easy.

Tragically, however, calculating N_j is not necessarily an easy manner. Consider the possible methods of populating level j:

Electron collision	$e + I_{gr} \to e + I_j$
Proton collision	$p + I_{gr} \to p + I_j$
Radiative recombination	$e + I_{gr}^{+} \to I_j$
Radiative transition	$I_k \to I_j + \gamma$
Dielectronic transition	$e + I_{gr}^{+} \to I_n^{*} \to I_j + \gamma$
Innershell excitation/ionization	$e + I_{gr}^{-} \to 2e + I_j$

And then there are the depopulation methods:

Electron collision	$e + I_j \to e + I_{gr}$
Proton collision	$p + I_j \to p + I_{gr}$
Radiative transition	$I_j \to I_{gr} + \gamma$

In collisional ionization equilibrium, we assume that the ion abundance is constant and so can solve for the level population by simply balancing the rate equations between the levels while requiring the level population to sum to unity.

However, in the case of a supernova remnant, equilibrium may be a poor assumption, and a time-dependent method must be used. In this case, the true solution is to assume only that atoms are conserved, and solve for the level population of all the ions at once.

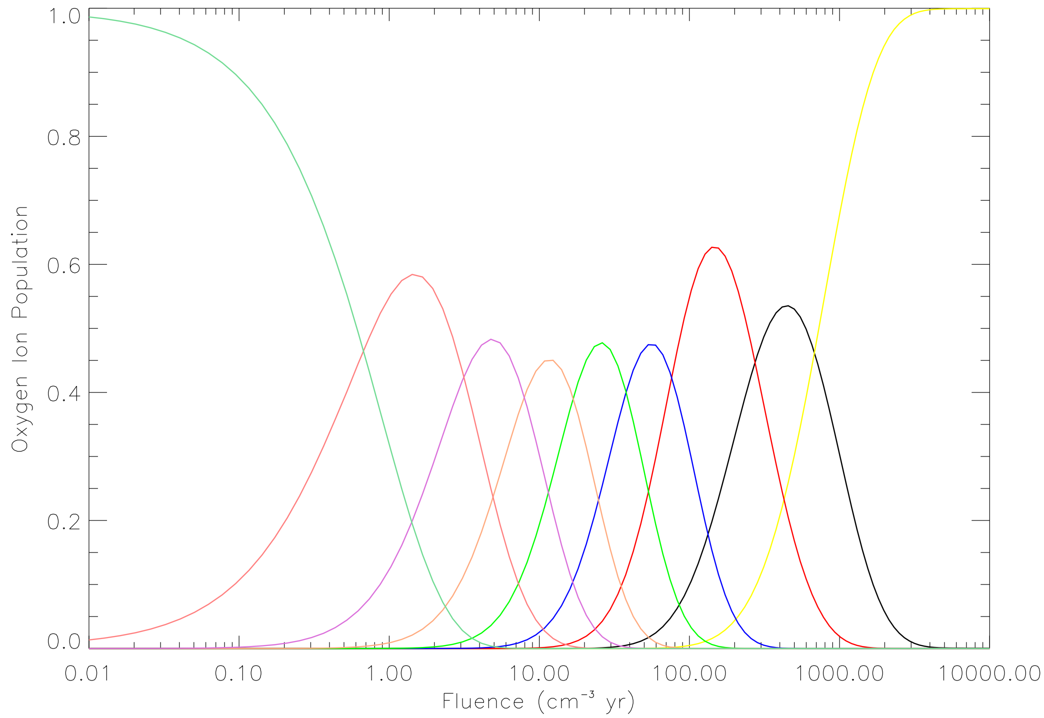
This is usually *not* done, because the total ion-to-ion rates are generally known to better accuracy than the per level rates. Instead, a two-step approach can be used:

1. evolve the ionization state and
2. Solve for each ion's level population using the ion balance from (1).

Note: Since all of the atomic rates in question are proportional to time and electron density, it is convenient to use the fluence, defined as

$$f = \int n_e(t)dt \tag{3}$$

as the dependent variable for non-equilibrium ionization situations.


1.0
0.8
0.6
0.4
0.2
0.0
Oxygen Ion Population
0.01
0.10
1.00
10.00
100.00
1000.00
10000.00
Fluence (cm⁻³ yr)

And now, summing up with things both said and unsaid:

- ISM gas emission is nearly impossible to measure
- ISM absorption studies, using high-resolution spectra, are more promising (but I didn't have time to discuss them)
- X-ray halos are a powerful new(ish) way to measure dust grain properties
- Line ratios are far cleaner, and with Chandra/Newton CCD resolution, worth extracting.
- Modelling an ionizing plasma requires ionization rates and the high-T behavior of excitation rates. These are fairly well-known.
- Modelling a recombining plasma requires radiative and dielectronic recombination rates, as well as the near-threshold behavior of excitation rates. These are extremely poorly known.
- Using DR lines for SNR diagnostics will not be possible anytime soon, except possibly for SNRs small and bright enough to be done with gratings.
- Fitting the continuum above 1 keV is a decent way to get a baseline electron temperature.